Flex4RES

Flexible Nordic Energy Systems

Framework conditions for flexibility in the Gas – Electricity interface of Nordic and Baltic countries

A focus on Power-to-Gas (P2G)

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Flex4RES project summary

The Flex4RES project investigates how an intensified interaction between coupled energy markets, supported by coherent regulatory frameworks, can facilitate the integration of high shares of variable renewable energy (VRE), in turn ensuring stable, sustainable and cost-efficient Nordic energy systems.

Through a holistic system approach based on coupled energy markets, we identify potentials, costs and benefits of achieving flexibility in the Nordic electricity market created by the heat, gas and transport sectors as well as by electricity transmission and generation. Flex4RES develops and applies a multidisciplinary research strategy that combines technical analysis of flexibility needs and potentials, economic analysis of markets and regulatory frameworks, and energy system modelling that quantifies impacts.

Through the development of a coherent regulatory frameworks and market designs that facilitate market interactions, which are optimal for the Nordic conditions in an EU context, transition pathways to sustainable Nordic energy systems are identified. Flex4RES will comprehensively discuss and disseminate the recommended pathways and market designs for achieving a future Nordic sustainable energy solution with a variety of stakeholders from government, industry and civil society.

More information regarding the Flex4Res project can be found at www.Flex4RES.org or by contacting project manager Klaus Skytte at klsk@dtu.dk

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Framework conditions for flexibility in the Gas – Electricity interface of Nordic and Baltic countries

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Problem Statement

- Power to gas (P2G) or the transformation of electricity into a gaseous state, like hydrogen or methane, is a relevant flexibility option for power systems operating with substantial shares of variable renewable energy (VRE) sources.
- It is particularly relevant in situations in which the excess supply of renewables relative to demand induces low electricity prices, such that electrolysis becomes cost-efficient to produce hydrogen.
- The latter can be stored for later use in the reconversion to power and heat, i.e. in the "round trip" application of P2G. Alternatively, it can be used as input in the production of methane, which can be injected directly into the gas network. Overall, the whole P2G supply chain creates interactions between the power and gas systems, but also with heating and transport.
- The central goal of the study is to identify the *framework conditions* for P2G as a flexibility option in the Nordic and Baltic countries. However, for each country under investigation, the study departs from an analysis of existing *system conditions* which facilitate the application of P2G as a flexibility option.
- More precisely, *framework conditions* refer to the existing conditions in the taxation, regulatory and market environment, which represent barriers or drivers for the development of P2G as a flexibility option. Identifying these is important to target policy decisions.
- In contrast, *system conditions* refer to aspects that reflect the structure of the energy system, and are not easily modifiable in the short run. In particular, we focus on the existence of a well-developed gas infrastructure and the expected reliance of the studied power systems on intermittent renewables, such as wind and solar. If both system conditions are present, we consider that a given power system *may* be able to benefit from P2G as a flexibility option. However, the consideration of system conditions is just indicative and without detriment to other flexibility options, such as interconnections, which could be more efficient than P2G applications.
- Moreover, the need for flexibility is not strictly related to these system conditions, as flexibility needs originate from the region as a whole. For example - given that the Nordic/Baltic power market is already integrated and if suitable hydrogen storages existed - it would be suitable to produce hydrogen in Sweden in response to peaks in wind power in Denmark, and vice-versa.
- From a technological perspective, we focus our attention on the "round trip", that is: electrolysis → storage of hydrogen → power and heat production from hydrogen, as one of the possible steps along the P2G supply chain. An alternative path, which we also consider, is using hydrogen input in the upgrading of biogas, which results in synthetic natural gas and can be injected directly into the existing gas network.

Key Findings

- However, none of the countries have hydrogen storages available at a scale that is large enough for the round trip to be applicable.

- Our analyses show that Denmark is a country that presents the system conditions required to make of P2G a suitable flexibility option. It has a well-developed gas infrastructure, including sizeable storages, and has a power system that already consumes more than 40% of wind power; a share that is expected to increase in the years to come.
- While there are important drivers for P2G in Denmark, such as a favorable taxation framework for the electrolysis process and the availability of subsidies for methanation, there are also significant barriers. For example, transmission and distribution grid costs (per unit of energy) are considerably higher than in some of its Nordic counterparts, like Sweden and Norway. This constitutes a barrier for the profitable production of hydrogen and its reconversion into electricity and heat.
- The presence of the Public Service Obligation (PSO) charge in Denmark – which will be progressively phased out between 2017 and 2022 – is another important barrier for P2G applications. Our quantitative analyses show how the reduction of this charge will improve the business case for all P2G applications considered in the study.
- We also find that all the Baltic States have considerably favorable system conditions for the relevance of P2G as a flexibility option. Not only do they possess well-developed gas infrastructures – including an important underground storage in Latvia – but they are expected to increase the share of intermittent renewable output in their systems. However, their focus on gaining independence from its traditional supplier of natural gas may collide with the development of P2G applications, as the focus tends to be on *supplier* substitution rather than on *fuel* substitution. This may tend to create a lock-in into specific natural-gas fueled technologies in electricity, heat and transport.
- Despite favorable system conditions, the framework conditions for the development of P2G are not ideal in the Baltic States. Taxes, PSO charges and elevated grid costs make the "round trip" between hydrogen production via electrolysis, and the reconversion to electricity and heat very costly.
- In the remaining countries of the study (Finland, Sweden and Norway), the system conditions are somewhat diverse. Finland and Sweden have an established natural gas system, but it is not as developed as it is in the Baltic States or Denmark. Norway relies on hydropower and is a major player in the global oil and gas business. It operates one of the largest international gas transportation systems in the world, and yet it does not have a domestic gas network. Moreover, among Finland, Sweden and Norway; Sweden is the country that is expected to rely more on wind generation. In contrast, both Finland and Sweden have nuclear power, and hydropower plays a non-negligible role.
- However, the framework conditions for P2G applications are favorable in Finland, Sweden and Norway. Our quantitative analysis show that in terms of marginal cost for the round trip, Sweden, Finland and Norway possess the lowest among all countries under analysis.
- In summary, it is somewhat paradoxical that the countries with the best system conditions do not have ideal framework conditions. Conversely, the countries with less-than ideal system conditions for P2G, have favorable framework conditions.

- As policy recommendations, the study suggests to focus primarily on grid costs, PSO charges and taxation frameworks to make of P2G a feasible flexibility option. Introducing subsidies at the production stage may be advisable if an alternative to tariffs, taxes and other surcharges does not render a solid business case. Subsidizing the investment cost in P2G applications – which is not discussed in detail in this report – may also be a less market intrusive solution.

CONTENT

1. Introduction

This report focuses on the framework conditions for flexibility at the interface of the gas and electricity systems of the Nordic (Denmark, Finland, Norway, Sweden) and Baltic (Estonia, Lithuania, Latvia) countries.

By *framework conditions*, we refer to the regulatory and market arrangements that either facilitate or hinder any flexibility option. However, the departure point of our analyses are *system conditions*, which refer to aspects that reflect the structure of the energy system, and are not easily modifiable in the short run. In particular – in the present report – we focus on the existence of a well-developed gas infrastructure and the expected reliance of the studied power systems on intermittent renewables, such as wind and solar. If both system conditions are present, we consider that a given power system will be able to benefit from P2G as a flexibility option.

However, the consideration of system conditions is just indicative and without detriment to other flexibility options, such as interconnections, which could be more efficient than P2G applications. Moreover, the need for flexibility is not strictly related to these system conditions, as flexibility needs originate from the region as a whole.

Because of its heat content and cost-effective storability, gas is a flexible fuel with many applications in the industry and the power sector. The energy vector from gas to power and its implications for flexibility have been explored to some extent in the Flex4RES report on framework conditions for district heating [1], where Combined Heat and Power (CHP) power plants play a central role.

In the present report, we focus on the converse energy vector from power to gas (P2G), which refers to the transformation of electrical power into a gaseous (thus, storable) energy carrier [2]. Final uses of these renewable gases are for electricity production, transportation, district heating and other industrial applications. However, due to its relevance for power system balancing, we will emphasize on the “round trip” application of P2G. That is to say: hydrogen produced through water electrolysis, which can be stored in special facilities, and later be injected into the gas network (provided that technical restrictions are met) or reconverted into electricity via fuel cells or hydrogen combustion. Another P2G application in which hydrogen plays a central role is the methanation of biogases, which allows producing a renewable gas with equivalent properties to natural gas, thus allowing to take advantage of the existing natural gas infrastructure (storages and gas network) of the countries in question.

1.1 Research questions

The present report poses the two following *general* research questions:

- What are the existing framework conditions for flexibility in the P2G interface in the Nordic and Baltic countries?

- What measures can be taken to increase the value of flexibility sourced from P2G?

The quantitative analysis presented in the report answers the following specific questions. In relation to *all the countries in the study* in the “round trip” application of P2G:

- What are the short-term marginal costs of producing hydrogen via electrolysis with energy content of 1 MWh in all the countries of the study, while considering all applicable taxes, subsidies and grid tariffs?

- What are the short-term marginal costs of producing electricity using the hydrogen from the electrolysis process as input in a Fuel Cell?

In relation to *Denmark only*:

- What makes the difference between the marginal production cost of 1 MWh of electricity from a Combined Cycle Gas Turbine (CCGT) running on natural gas vs. a Fuel Cell running on hydrogen in Denmark?

- What is the marginal cost of producing 1 MWh of biomethane in Denmark while considering all applicable taxes, subsidies and tariffs?

The findings of the report indicate both the current situation regarding P2G as a flexibility option in the Nordics and Baltics, and also gives guidance for potential measures to increase the value of P2G as a flexibility option.

1.2 Report contents

Including the introduction, the report consists of six sections. Section two makes a delimitation of P2G technology, and specifies what are the technologies involved in every step of the P2G value chain. Section three defines the methodological approach to answer the posed research questions, while section four, presents a description and analysis of the existing framework conditions for P2G in each of the Nordics and Baltic countries. Section five presents the results of a quantitative analysis in which we first focus on all the countries to estimate the short-term marginal cost of the round trip, including all applicable taxes and tariffs. Later, within the same section, we focus on Denmark alone to present a comparison of the marginal production cost of electricity from a CCGT running on natural gas vs. a Fuel Cell running on hydrogen. In an additional subsection, we also present estimations for the marginal cost of 1 MWh of biomethane in Denmark. Finally, the sixth section concludes and makes policy recommendations to increase the value of P2G as a flexibility option.

2. Technological delimitation of Power to Gas (P2G)

In general terms, P2G refers to the conversion of electricity to a gaseous state, such as hydrogen or methane [2]. This implies that in situations of a power system with high shares of VRE where there is excess supply relative to demand, power can be converted into gas and then be stored, injected into the gas grid or used in a number of applications, such as transport. Because the focus of Flex4RES is on the balancing challenge of the power system on an hourly basis, this report focuses on the kind of applications that are relevant for this challenge. In particular, we refer to the Nordic and Baltic power system, which is in the middle of an ambitious green transition, involving a greater reliance on non-dispatchable technologies.

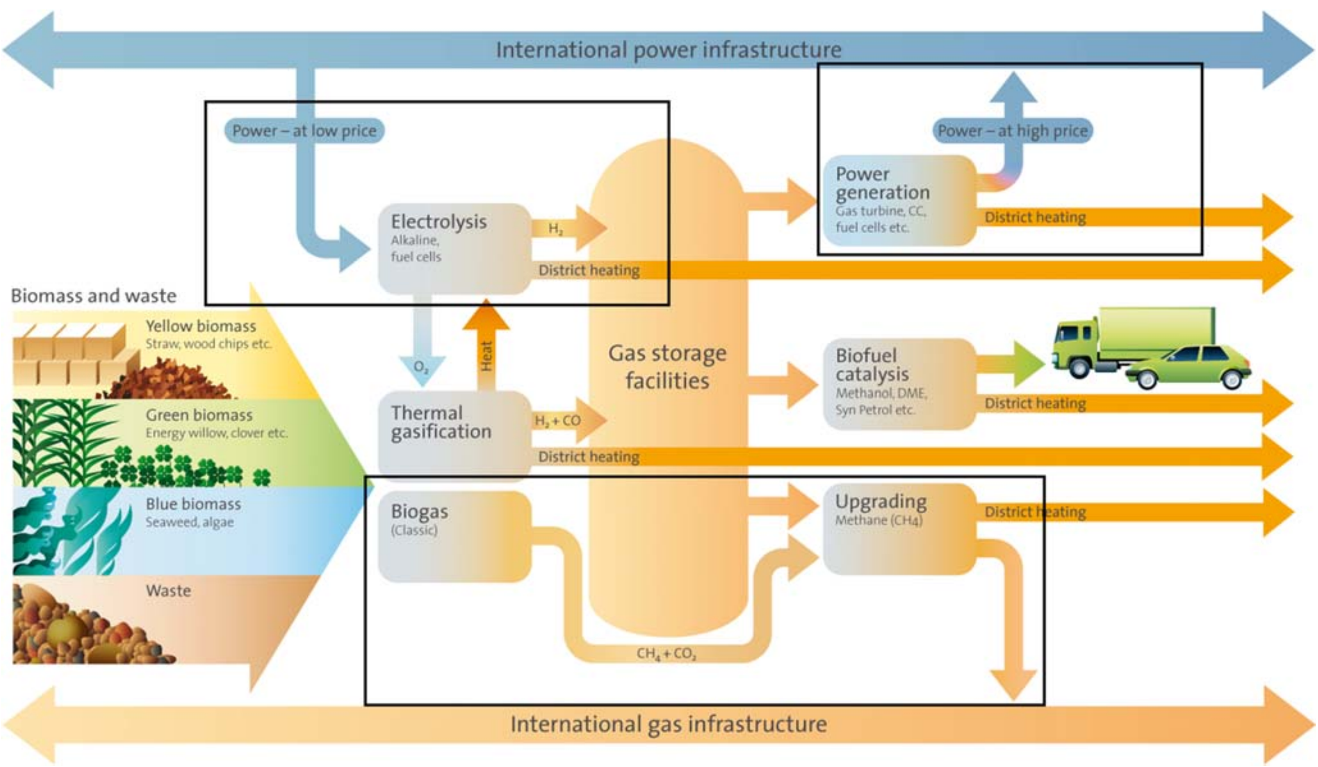

Figure 1: Relationship between the electricity and gas systems. Source: energinet.dk

The following are the specific technologies (see Figure 1) on which we will focus our analysis:

2.1 Electrolysis

Electrolysis, and more specifically the electrolysis of water, is the decomposition of water into its chemical elements, namely oxygen and hydrogen gas, due to an electric current being passed through the water. The longest-standing of the available technologies for water electrolysis is alkaline electrolysis (AE), which has existed since the late eighteenth century, and is commercially available. Two other highly efficient but less mature technologies are the solid oxide electrolyser cell (SOEC) and the Proton Exchange Membrane (PEM) cell. The inputs to the electrolysis process are water and electricity, while the outputs are oxygen and hydrogen, which is as clean as the energy source from which it is produced (see the upper left part of Figure 1) [3].

2.2 Hydrogen storage

According to [3], hydrogen can be stored in five different ways. First, in pressurized form (in caverns, tanks and pipelines); second, in liquid form (in cryo-tanks); third, via absorption; fourth, in chemical compounds, such as synthetic natural gas (SNG), ammonia, and synthetic liquid hydrocarbons; fifth, via adsorption. For the analysis of this report, we will assume that a storage facility exists, i.e. we will not analyse the implications of *investing* in these facilities. Furthermore, we will work under the (rather strong) assumption that such storage is available at a negligible cost.

However, it is important to note that the operators of the gas infrastructure of several European countries limit the volume of hydrogen in the gas network. According to [4], by volume/molar percent, Sweden allows less than 1%; Austria and Switzerland 4%; Germany 10% and Holland 12%. In contrast, countries like the United Kingdom and Belgium, allow 0%. Safety is a major source of concern for operators, given that hydrogen is a very volatile gas, which is highly flammable [5].

2.3 Power and heat generation with hydrogen as fuel

Hydrogen from electrolysis can be reconverted to power and heat through a number of technologies. Because of its technical efficiency levels, fuel cells, with a total efficiency of 92% (heat and electrical efficiency) by 2020; and combined cycle gas turbines (CCGT), with an electrical efficiency of around 50% by 2020, are well-suited to generate both power and heat [3], [6].

Regarding fuel cell technology, we focus our attention on PEM fuel cells, whose fuel options are limited to hydrogen and methanol [3]. In the case of CCGT, the use of hydrogen is not widespread but it is indeed possible, as documented by [7].

2.4 Methanation

This process refers to the reaction by which carbon oxide and hydrogen are converted to methane and water. In this report we focus on the production of synthetic natural gas (SNG) through the methanation of biogas, as described by [8]. There are two main inputs in this process: electricity and biogas. The core unit in a methanation plant is the hydrogenation/methanation unit in which carbon dioxide is converted to methane by reacting with hydrogen. An important aspect of methanation output is that synthetic natural gas does not have technical limitations to be fed into the existing gas infrastructure. That is: the technical restrictions that happen as a result of feeding in hydrogen are not present anymore.

3. Methodology

This section presents the methodological approach of the report and clarifies relevant concepts.

3.1 Definition of flexibility

As in other Flex4RES studies [1], [9], flexibility is defined in this report as a measure to keep the balance between generation and consumption of electricity, since the variability in generation and in consumption is to be balanced in flexible supply and in flexible demand. In connection with this definition, P2G is a multi-faceted flexibility option, closely connected to demand-side, storage and supply-side measures to enable flexibility. On the demand side, it is relevant when intermittent sources are relatively abundant, at which times storages build up. It uses existing stocks to produce at times when renewables are relatively scarce.

From an *operational* perspective, P2G becomes relevant in situations where there is excess VRE supply relative to demand in the power system and, therefore, electricity prices decrease. Provided that storages exist, these stock up when input prices, i.e. electricity prices, are low and release output for power generation when prices are high (see Figure 1).

3.2 Review of statistical information and national regulations with impact on P2G

One aspect of the study is *documental* in nature, as it relies on a review of statistical information and existing national regulations which may act as either drivers or barriers from P2G as a flexibility option in the Nordic and Baltic countries.

To understand the *system conditions*, we investigate quantitative information in relation to the installed power capacity, electricity generation for recent years, and the degree of development of the gas network.

The review of the existing national regulations aims at identifying the *framework conditions*, and focuses on the following concrete aspects with regard to the operational cost of P2G as a flexibility option:

- Whether the inputs (i.e. electricity) to P2G in any of the phases of the P2G value chain receive a favourable tax scheme
- Whether any of the steps in the P2G value chain obtain support. For example, if electrolysis, storage or methanation receives any kind of subsidy aimed at reducing the cost of production.
- Whether the technical requirements of gas infrastructure operators limit the possibility of injecting hydrogen into the gas grid

Regarding the *investment* in P2G technology, we acknowledge the fact that it is a flexibility option that still is at the research and development stage, despite the fact that some of the specific steps in the supply chain have quite mature technologies, e.g. Alkaline electrolysis. In consequence, we survey:

- Whether there are any explicit investment incentives in P2G technology in the form of subsidies

3.3 Quantification of the operational cost of P2G

Another aspect of the study is quantitative in nature and focuses on estimating the short-term marginal cost of production along the P2G value chain. We conduct the analysis in the following steps:

3.3.1 Transforming electricity into hydrogen: comparison of all countries

At this stage, we collect all taxes, subsidies and grid tariffs on electricity generation to obtain the cost of electricity input in the electrolysis process *in all countries of the study*. Assuming the efficiencies of electrolysis given by [4], we estimate the output cost of hydrogen with 1 MWh of energy content. We compare this cost with that of an alternative fuel with equivalent energy content, namely natural gas.

3.3.2 Comparing electricity and heat production costs in Fuel Cells vs. CCGT: the case of Denmark

At this stage we calculate the cost of producing 1 MWh of energy output, as electricity and heat in a Fuel Cell with hydrogen input vs. natural gas input, including all taxes and grid tariffs *applicable in Denmark*. As additional reference, we calculate the output cost of a CCGT plant running on natural gas. At this stage, the costs estimated in the electrolysis step are the input costs, and the output cost of 1 MWh of electricity including taxes, subsidies and tariffs. The technical information for this stage of calculations comes from [6].

3.3.3 Methanation: the case of Denmark

At this stage, we estimate the cost of producing 1 MWh of SNG and compare it with the cost of natural gas in Denmark. As with the other steps, we estimate the cost of input, which includes biogas and electricity, and add all tariffs, subsidies and taxes to this cost. With the technical information in [8], we estimate the cost of producing SNG and compare it with cost of Natural Gas.

Further details can be found on section 5 of the study and the appendix.

4 Review of framework conditions for P2G in the Nordic and Baltic countries

4.1 Denmark

Among the countries that are subject of study in the Flex4RES research project, Denmark presently has the highest share of wind power by electricity generation, i.e. 42% as a share of annual consumption in2015 [10]. According to the Nordic Energy Technology Perspectives (NETP) baseline scenario [11] in 2050, Denmark will be the country with the second highest share (65%) of wind power production among Nordics and Baltics, exceeded slightly only by Lithuania (66%). The reliance on intermittent sources like wind constitutes one important system condition for the potential relevance of P2G in this country.

Another relevant system condition is the existence of a well-developed natural gas system in the country. Overall, the Danish gas network transports approximately 8 billion m^3 in a year from the Danish North Sea production sites to the end-users and the rest of Europe, via a treatment plant and a 17,000 kilometer distribution network [12]. Moreover, Denmark has two gas storage facilities with a total capacity that adds up to roughly one third of the Danish yearly electricity consumption, e.g. 10,769 GWh in the year 2017-2018 [13], [14].

Regarding framework conditions for the operation of P2G in Denmark, these are mostly favorable. In particular, we have found the following drivers:

- *There is a positive taxation framework for electrolysis.* According to Danish tax legislation, electrolysis is part of a process usage of energy in which an input is transformed into an output with added value and, thus, can generally be exempted from some of the usual taxes on electricity and other fuels. Furthermore, electrolysis is considered a “special process”, and thus obtains the lowest possible electricity tax rate [15].

- *Electricity output from hydrogen has a relatively more favorable tax framework than alternative fuels, like natural gas.* This is because hydrogen gas is a cleaner fuel than natural gas and is, thus, exempt of most of the environmental taxes [15].

- *Denmark has established a subsidy scheme, specifically oriented to upgraded biogas*, implying that methanation can obtain a subsidy on the methane content of the SNG output. [16]

However, there are also barriers:

- Large-scale hydrogen storages are not available in Denmark.

- *The presence of grid tariffs and the PSO charge*, which will be progressively abolished between 2017 and 2022, is a significant barrier for the round trip P2G application.

- *There is no subsidy for electrolysis in Denmark.* In spite of the favorable taxation framework present in Denmark, there could be a more solid business case if electrolysis received support.

- *A clearly defined business model for P2G does not exist yet in Denmark*. In consequence, this implies that energy policy does not yet have a clear vision if P2G should be supported, where in the value chain the support should go to, and where the economic gains from learning should be incentivized.

Despite the aforementioned barriers, Denmark is the only country with MW-scale P2G demonstration projects in the Nordic and Baltic region. This means that research and development funds, with co-financing from relevant players in the private sector, are flowing into Danish P2G. One of the largest is the BioCat Project, which has a 1 MW capacity Alkaline electrolyser that participates in the electricity wholesale market by providing frequency regulation services to the local power grid. The output of the electrolysis process is then fed into a methanation system that later injects it into a gas distribution grid [17]. Another large demonstration project is the HyBalance, which will deploy a 1.2 MW PEM electrolysis facility during 2017. In partnership with a balancing responsible party, the project will demonstrate how an electrolyser can operate as a flexibility resource for ancillary services procured by the Danish transmission system operator [18].

4.2 Estonia

Domestic electricity generation in Estonia is heavily dependent on oil shale, which consistently ranks as the single most important fuel for the thermally-dominated installed capacity of the country [9]. In 2015, for example, oil shale accounted for 75% of domestic electricity output. However, in parallel to Estonia's dependence on fossil fuels, the number of installed wind turbines has increased over time and by the end of 2015 accounted for approximately 13% (300 MW) of the country's total installed capacity. Wind power output represented roughly 9% of domestic generation in 2015 [19] and according to projections, this number is set to increase. According to the NETP baseline scenario [11], wind power will represent over 40% of output in 2050. With the increasing role of wind power, the potential for developing P2G as a flexibility option in Estonia is present.

Furthermore, Estonia possesses a well-developed gas network with connections to both Russia and Latvia, and imports from Russia and Lithuania through the Klaipeda Liquefied Natural Gas (LNG) terminal, which opened in 2014. However, Russian supplies remain dominant and both diversification of suppliers and the integration to the rest of Europe hinges on the completion of important infrastructure projects, such as the Balticconnector which links Estonia and Finland, enabling a bi-directional transmission capacity of 7.2 million cubic metre (72 GWh) per day [20]. Importantly, the completion of the Balticconnector project will coincide with the reinforcement of the Estonia-Latvia gas interconnection, and the connection between Poland and Lithuania. These projects are being prioritized and economically supported by the European Union (EU) with the goal of facilitating energy independence from Russia and the creation of a common EU gas market. In summary, the expansion of the Estonian gas network is underway, creating another important system condition, which creates the potential to develop P2G as a flexibility option.

However, the existing framework conditions for P2G as a flexibility option are not particularly favorable:

- *The presence of an elevated grid transmission and distribution cost, together with the existence of a PSO* significantly increases the cost of P2G in Estonia.

- *The taxation framework applied to electrolysis in Estonia is not particularly advantageous*, as it treats the process in the same way as any other electricity consumption. That is to say: there are no particular tax exemptions or reductions for the electricity input in the electrolysis process, where the tax rate applied is 4.47 EUR/MWh.

- *Electrolysis and gas upgrading are not currently subsidized*. However – concerning the latter – there is a governmental proposal to implement a temporary subsidy (93 EUR/MWh) for the production and sales of biomethane to any user, together with a favorable treatment for the usage of this fuel in the transport sector (100 EUR/MWh). By 2021, the support mechanism is expected to be in the form of quotas, i.e. an obligation on retailers to supply at least 4% of total gas sales as biomethane.

Furthermore, as barriers we identify:

- *The absence of significant gas or hydrogen storage facilities in Estonia, together with a considerably stringent requirement for the volume of hydrogen in the gas network* (less than 0.1% in molar percent)

- *The absence of a clearly defined business model for P2G in Estonia,* where it remains unclear if it will be developed as a flexibility option, let alone the specific applications that will be supported.

- *Large-scale hydrogen storages are unavailable in Denmark.*

If any, the following is a driver we have identified:

- Although power plants running on hydrogen are not subsidized in Estonia, *the presence of both carbon and nitrogen oxide taxes on natural gas gives a relative advantage to hydrogen as a fuel for power generation*.

4.3 Finland

The total installed electrical capacity of Finland was 16,749 MW at the beginning of 2015, with a leading role for CHP plants (44.1%), followed by hydro (18.8%) and nuclear (16.4%). The remaining capacity was composed of condensing power (9.5%), gas turbines and engines (6.9 %), wind power (3.8%) and other small-scale production (0.5%). By source of generation, CHP produced 31.1% of electricity generated, while nuclear accounted for 33.3% in 2015 [9]. Furthermore, 2014 figures from the International Energy Agency (IEA) reveal that natural gas accounted for 8% of all electricity generated, and 17% of all heat produced in the country.

While the transmission network is mostly developed in the southernmost part of the country, close to consumption centers, the Finnish natural gas system is well-developed and is presently being expanded. First, it is the home to a LNG terminal in Pori (opened in 2016), which supplies gas for maritime transport and industrial uses. Second, Finland lies at one end of the link between Finland and Estonia (the Balticconector project) which is a crucial element in the integration of Nordics and Baltics, as well as the development of a common EU Gas Market.

Although still negligible, the role of wind power is growing rapidly: relative to 2014, installed wind power capacity grew by 59% in 2015 and output from this source increased by 110.8% [9]. The NETP baseline scenario foresees wind power to account for 13% of Finnish generation by 2050, that is, the third most important source of generation after nuclear and hydro [11]. Compared to other countries in the Nordic/Baltic region, like Denmark or Lithuania, the challenge of intermittency is expected to be less pressing.

However, Finland does have the system conditions for P2G to be a relevant flexibility option but – given the Finnish technology mix – power generation may not be the most important application. The technical conditions and expertise for hydrogen production via electrolysis, natural gas reforming, biogas production and gas upgrading are present in Finland through various companies that work in the area. For example, Woikoski owns the largest facility in Europe to produce hydrogen by means of water electrolysis [21], and partners in the development of sustainable hydrocarbons used in the production of fuel and plastic in the SOLETAIR project [22].

While the framework conditions for P2G are not particularly favorable, they do not represent an evident barrier either. Specifically:

- *The electricity tax applied to electrolysis in Finland corresponds to the second (industrial) class in which the applicable tax rate is lower than in other sectors, like households.* However, this tax rate (7.03 EUR/MWh) is considerably higher than in other countries of the region. In particular, when compared to countries like Denmark, Sweden and Norway.

- *Electrolysis and production of upgraded gas are not currently subsidized*. However, output from CHP plants running on biogas are eligible for a "heat bonus", which is an additional incentive on top of the feed-in premium applied in Finland for electricity production. Furthermore, the Finnish government supports investment in "excellence projects for energy", where fuel production projects are among the eligible activities.

The main barrier we have identified is the following:

- *P2G is recognized as a relevant electricity storage option* by the Finnish Parliamentary Committee on Energy and Climate Issues [23], but apart from an indication of its relevance as a transport and power generation fuel, *there are no specific policies to support its development nor a clear vision of the specific applications to support*.

- Large-scale hydrogen storages are not available in Finland.

As the main driver for the development of P2G applications in Finland is:

- *The vast experience on the development and integration of biofuels into the Finnish energy system*, which can easily be combined with upgrading and easily be set as a P2G application that can obtain support.

- Relative to other countries, in the region, *grid costs are not as high*. Furthermore, there is no PSO charge in Finland.

4.4 Latvia

At the end of 2014, the total installed capacity of Latvia (approximately 2.9 GW) was composed, in its majority, of thermal generation (approximately 42%) and hydropower (around 54%) with a marginal but increasing role for wind power (2%) [24]. As part of the country's thermal generation capacity, there is a rather small but increasing number of biogas and biomass CHP plants [25]. But upon observation of the Latvian gross domestic electricity generation in 2014 (5141 GWh), it is possible to confirm that the single most important fuel used in the country is natural gas, with 45% of the total. While the remaining 55% are renewables (mostly hydro and a minor but increasing role for biofuels and wind), electricity generation in Latvia is still dominated by one fossil fuel, namely natural gas. [26].

On the other hand, as is the case of countries like Denmark, Estonia and Lithuania, the system conditions for the development of P2G are also present in Latvia. First, there is a well-developed gas network in the country with interconnections to Estonia, Russia and Lithuania. Of particular relevance is the fact that Latvia is home to the only underground gas storage facility in the Baltic States – located in Incukalns – with a capacity of 2.32 billion m³ active, or regularly extracted, natural gas [27]. The completion of the Balticconnector project will also allow countries like Finland to benefit from this facility. Second, variable renewables (i.e. wind) are expected to gain relevance in the country's electricity system, as part of its renewable action plan. In fact, the NETP baseline scenario foresees that by 2050, wind power will account for approximately one-half of its total electricity output [11].

However, favorable framework conditions for the emergence of P2G as a flexibility option are not present in the country:

- *The taxation framework applied to hydrogen production via electrolysis (1.01 EUR/MWh), together with elevated grid costs is not particularly favorable*, as there are no particular exemptions to consumers of electricity who transform their input into a gaseous energy carrier.

- *Electrolysis and gas upgrading are not currently subsidized.* However, until 2016, biogas production (an element of the value chain in the methanation process) was subsidized when distributed to the natural gas network, but the subsidy is not currently in force.

As barriers for P2G in Latvia, we identify:

- The considerably *high grid costs, together with the presence of a PSO charge* elevate the cost of P2G applications.

- *The considerably stringent requirement for the volume of hydrogen in the gas network* (less than 0.1% in molar percent).

- *The absence of a clearly defined business model for P2G,* in which it remains unclear what kind of policy will be implemented to develop it as a flexibility option and the specific applications that will be supported.

- *The absence of hydrogen storages*

The only driver we identify in the framework conditions for P2G in Latvia is:

- *The presence of both carbon and nitrogen oxide taxes on natural gas, which gives hydrogen advantage relative to natural gas.*

4.5 Lithuania

At the beginning of 2016, the total installed capacity of the Lithuanian power system was 3.5 GW. The largest share was fossil-fired CHP (54%), followed by hydro (29%), wind (12%) and other forms of renewable-based electricity generation (5%), including biomass, biogas, waste and solar PV power plants. In 2016, gross domestic generation was 3974 GWh, where the largest share (35%) was produced by thermal-based power plants, followed by wind (28%), pumped storage (14%), hydro (11%) and other renewables (11%). Nonetheless (since the nuclear phase-out), domestic electricity production usually covers around one-third of Lithuania's electricity demand, thus relying on imports from neighboring countries to cover the deficit; where Latvia, Estonia, Finland, Sweden and Poland supply the majority [28].

The aforementioned description illustrates the fact that, despite the substantial progress of renewables – particularly wind – Lithuania's electricity system still depends on fossils and natural gas remains the single most important fuel for electricity generation [29]. On the one hand, this implies that a well-developed natural gas network exists, with interconnections to Latvia, Belarus and the Kaliningrad Region of Russia. This, alongside an expected substantial increase of wind. In fact, the NETP perspectives' baseline scenario expects that by 2050, over 66% will be accounted to wind power; above the 65% share foreseen for Denmark [11]. Thus, the two pre-conditions for P2G as a relevant flexibility option exist in Lithuania. On the other hand – despite efforts to gain independence from Russian gas – natural gas tends to prevail in the energy economy, as the Klaipeda liquefied natural gas (LNG) storage and regasification unit inaugurated in 2014 illustrates. That is: rather than a strategy aimed at *fuel* substitution, Lithuania seems to be aiming at *supplier* substitution.

As in the rest of the Baltic States, favorable framework conditions for the development of P2G as a flexibility option are essentially absent.

- *Electrolysis and gas upgrading are not currently subsidized.* However, biogas production - an element of the methanation value chain – is subsidized in Lithuania [30].

- *There are no gas storage or hydrogen facilities in Lithuania* but there is an important project underway, i.e. the Syderai Undergrund Gas Storage [31]. Furthermore, the existence of the Klaipeda LNG facility could allow for the production of hydrogen via natural gas reforming, as documented in [32] and [33].

If any, drivers for P2G in Lithuania as a flexibility option are:

- *The presence of a favorable tax system* which, although not directly aimed at improving the business case of electrolysis, exempts from electricity taxes any production process in which over 50% of the unit production cost can be accounted to electricity input.

- *The presence of carbon tax on natural gas, which gives hydrogen an advantage relative to natural gas.*

However, the main barrier for P2G in Lithuania is:

- *The absence of a clearly defined business model for P2G,* and it remains unclear what kind of policy will be implemented to develop it as a flexibility option or the specific applications that will be supported.

4.6 Norway

Norway is the hydro powerhouse of the Nordic and Baltic region. With a peak net load of 33,697 MW in 2014, hydro accounted for 31,240 MW (92.7%), followed by thermal capacity with 1,597 MW (4.7%) and wind with 859 MW (2.5%). Total electricity production was 142 TWh in 2014, of which 95.9% (136.2 TWh) was hydro, 2.5% (3.6 TWh) was thermal and 1.6% (2.2 TWh) was wind [9].

At the same time, Norway is a major player in the global oil and gas business. According to the IEA, as of 2016, it is the seventh largest producer and the third largest net exporter of natural gas in the world [34]. However, natural gas plays a very minor role in the production of electricity and heat, as 2014 figures from the IEA reveal [35]. In many respects, Norway is a peculiar country as it does not rely on natural gas – an abundant resource in the country – to produce electricity. As a matter of fact, such an option for electricity generation has proven to be highly contentious in the past [36], and it is quite unlikely that natural gas plays a greater role in Norway’s power sector at all. In fact, the construction of new natural-gas fired power plants is banned unless a Carbon Capture and Storage solution is in place [9]. Moreover, although it possesses and manages more than 8 thousand kilometers of gas pipelines from the Norwegian Continental Shelf to consumption centers, Norway lacks a domestic gas system.

Wind power currently plays a minor but increasing role in Norway, as between 2010 and 2014 the number of wind power installations has nearly doubled [9]. But because Norway has essentially met its renewable energy targets [37], wind power will only help to exceed them. According to the IEA’s NETP, around 19% of generation will be accounted to wind power by 2050, implying considerably less intermittency challenges than other Nordic and Baltic countries, like Denmark, Lithuania or Sweden, where the shares of intermittent renewables will be well above 40%.

In summary, we find that the system conditions for P2G as a *flexibility option for the power system* are not present in Norway. However, this does not preclude *transport applications*, which have been an important focus of the Norwegian energy policy. Aside from electricity production from hydrogen and methanation as technology options, the same framework conditions for electrolysis apply in the case of a transport application. Thus, in what follows, we focus on these.

We find that the situation in Norway is quite similar to the one in Sweden (section 4.7). In particular, we consider that framework conditions are favorable but not particularly aimed at the development of P2G. Specifically:

- *The taxation framework is favorable for electrolysis,* given that it is exempt from taxes.

- *Given the technology-neutral approach to renewable subsidies in Norway via the electricity certificate scheme, electrolysis can be easily supported*. On the one hand, hydrogen producers via electrolysis would pay a quota for renewable electricity consumed. On the other hand, renewable hydrogen aimed at producing transport fuel could receive additional income via the certificates they sell.

The main barriers for any P2G in Norway, including transport applications is:

- *The absence of a gas infrastructure, including storage and distribution facilities.* This applies even to the narrower use of hydrogen for transport purposes in Norway. As recently noted in Scientific American, it is not the Fuel-Cell economy but the lack of distribution infrastructure what prevents this technology from making a breakthrough. [38]

- The grid costs are not as high in Norway. In addition, there is no PSO charge in the country.

4.7 Sweden

In 2015, total installed capacity in Sweden added up to 39,313 MW, making it the largest electricity system of the Nordic and Baltic region. Peak hourly demand was 23,390 MW in 2015 and the four main technologies were hydro (41.2%), followed by nuclear (23.1%), wind power (15.3%) and CHP (9%). From a generation perspective, hydro (42.4%) and nuclear (41.1%) represented in 2014 the majority of the gross domestic electricity production in 2015. But right after these two sources, the third most important source was wind power, with 7.6% [9]. This figure is in line with the Swedish government's policy of diversifying the country's energy sources, while increasing the share of renewables [39]. In fact, according to the NETP baseline scenario, Sweden is expected to generate approximately 40% of its domestic production from wind power by 2050 [11]. Consequently, Sweden's power system will be subject to increased intermittency and will have more flexibility requirements. Thus, one of the system conditions for P2G to be a flexibility option exists.

On the other hand, the present role of natural gas in the production of electricity and heat in Sweden is rather limited. 2014 figures from the IEA show that natural gas accounted for only 0.3% of all electricity and 2.9% of all heat generated [40]. In addition, the existing Swedish gas network is of limited size (roughly 600 km), has no storage facilities, is limited to the southwest coast of the country and connected only to Denmark. However, the Swedish gas transmission system operator (Swedegas) is involved in a number of Smart Energy gas projects, including the development of an LNG terminal, biogas development and P2G.

In relation to the latter, Swedegas has joined efforts with representatives from the Swedish energy industry to conduct several studies to develop P2G in the country. In the first of these, the authors analyze the potential for P2G in Sweden and estimate that by 2030 – when the 30 TWh wind energy planning political target is achieved – between 2 and 3 TWh of biogas (methane) can be produced [41]. In the second study, the authors investigated the optimal location for a P2G demonstration study [42] and in the third [43], after the choice of the island of Gotland, they analyze the investment and operational costs of P2G, while considering several different applications and sources of revenue.

While the P2G concept appears to be gaining attention by Swedish energy industry and policy-makers, the existing framework conditions are favorable but not particularly aimed at developing P2G. In particular, we find that:

- *The taxation framework is favorable for electrolysis,* given that electrolysis is exempt from electricity taxes.

- *Given the technology-neutral approach to renewable subsidies in Sweden via the electricity certificate scheme, P2G applications can be easily supported*. On the one hand, hydrogen producers via electrolysis would pay a quota for renewable electricity consumed. On the other hand, electricity output from biomethane receives additional income via the certificates they sell.

We identify the following barrier:

- *Gas and hydrogen storage is not available in the Swedish network. Furthermore, the technical requirements for injection of hydrogen in the (limited size) Swedish gas network are stringent.* However, these requirements are less stringent than in other networks and the technical challenges are being investigated.

However, the main driver we find is that:

- *A P2G strategy is being designed in the context of the interaction between the main energy actors in Sweden*. While there is indeed a rather unclear vision of what a realistic P2G business model looks like, an analysis of potential owners and the future P2G value chain in Sweden is being considered, e.g. [43]

5 Quantitative analysis

In this section of the report, we use quantitative data regarding grid tariffs, taxes and subsidies to estimate the *operational* cost of P2G in the different stages.

In the first sub-section, we focus on the P2G "round trip". That is to say, transforming renewable electricity into hydrogen via electrolysis in times of excess renewable output, i.e. when electricity prices are relatively low, and then producing electricity and heat – with hydrogen as input in a fuel cell – during times of scarce renewable production, when electricity prices are relatively high. For comparison purposes, we perform this calculation across all the countries subject of the study: Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden.

In the second sub-section, we conduct a more detailed case study of Denmark, in which we evaluate all technological alternatives described in section 2 of the present report. This means that, in addition to the "round trip", we compare alternative (and well-established) ways of producing electricity and heat with natural gas as fuel. To this end, we consider all applicable gas network tariffs and taxes. Moreover, as a third option, we consider the production of biomethane, using electricity and biogas as inputs, and again include all applicable taxes and subsidies.

In summary, this section conveys a quantitative-based description of the framework conditions described in the earlier sections of the report.

5.1 Comparing the “round trip” in the Nordics and Baltics

This sub-section answers the following two questions:

- First, *what are the short-term marginal costs of producing hydrogen via electrolysis with energy content of 1 MWh in all the countries of the study, while considering all applicable taxes, subsidies and grid tariffs?*

- Second, *what are the short-term marginal costs of producing electricity using the hydrogen from the electrolysis process as input in a Fuel Cell?*

Implicit in the two questions is the assumption that storage is available for hydrogen, such that it is produced and stored when it is cost-effective to do so and is used at a later time. That is, when electricity prices are higher and intermittent installed capacity (e.g. wind power) is unable to produce.

To answer the first question, that is: to estimate the cost of transforming electricity into hydrogen, we add the following *input cost* entries, denominated in EUR/MWh:

1. *Nordpool System Price:* For the purpose of inter-country comparisons, which is our central goal, it suffices to assume a *fixed* value in all countries. In other words, we assume that the system price clears the whole market without differences in individual price zones.

2. *Electricity tax:* we investigate the electricity tax rate applicable to industrial and energy-related processes and if particular provisions exist in the legislation of each country in relation to electrolysis; specifically, the transformation of electricity into a different (i.e. gaseous) energy carrier or electricity-intensive processes in general.

3. *Grid costs:* this entry corresponds to the surcharges that a hydrogen producer would have to pay to the distribution system operator (DSO) and the transmission system operator (TSO) *per MWh* of electricity used. While the structure and level of grid tariffs across the Nordics and Baltics is quite diverse, we focus our comparison on the energy-related tariffs, ignoring capacity-based and other fixed charges present in several countries of the region. Moreover, given the existing differences across distribution tariffs within a given country, we have either averaged the tariffs (for Norway and Sweden) or have focused on a particular DSO in the country (Denmark, Finland, Estonia, Latvia, Lithuania). In all cases, we have relied on publicly available information published by the company or the country’s authorities. Overall, the grid costs considered in this entry attempt to convey a realistic picture of each country, but presents limitations in relation to the degree of detail and diversity.

4. *Public Service Obligation (PSO):* this entry refers to the charge per-unit of energy levied on electricity network users to ensure development of the electricity network and support to renewable energy development. It is present in all the Baltic countries and Denmark, where it will be progressively phased out between 2017 and 2022.

Once we have obtained a figure for the input costs to electrolysis, we rely on the following two technological assumptions. First, that by 2020, the PEM electrolysis technology will have an efficiency of electricity input to hydrogen output of 78%. This is in accordance with a recent study by a group of French researchers on the economics of P2G [4]. Second, that the hydrogen input to electricity output efficiency of a PEM cell is of 55%, while its hydrogen to heat output efficiency is 37%, such that the PEM cell's overall efficiency is 92%. These efficiency estimates originate from the Danish Technology Catalogue [3].

Having added the input costs to electrolysis and assuming that hydrogen is produced via PEM technology, and that electricity is produced in a PEM fuel cell, we are able to obtain the "round trip" disaggregated marginal costs and the implicit *minimum* sales (i.e. break-even) price for 1 MWh of electricity produced given that electricity wholesale price is zero. As mentioned earlier, for comparison purposes, it suffices to assume a fixed electricity system price. In this case, we assume that it is zero, in order to highlight the impact of all tariff and tax charges in addition to the price of electricity. Figure 2 illustrates the results obtained in more detail.

In Denmark (DK), for example, the minimum sales price of electricity *assuming that heat output has no economic value* (blue dot) is 117.6 EUR/MWh and the largest component of the marginal cost is the grid cost (orange share of the bar), whereas the smallest is the electricity tax (blue share of the bar). Note that the minimum sales price for Denmark (with no heat value) assumes that the PSO still is in place, but if we assume that is phased out – as will actually be the case in 2022 – the minimum sales price falls to 63.5 EUR/MWh. *Assuming that heat output does have an economic value* (and that the Danish PSO stands at the 2017 level), the minimum sales price (green dot) is 99.6 EUR/MWh.

At this stage it is convenient to clarify what is the economic value of heat that we have assumed for the calculations. While this depends on local aspects, such as the cost of heating fuel in a given area or the existence of a district heating network, we assume a "rule of thumb" value for heat sales. To this end, we rely on a recent study about P2G in Sweden, which estimates the cost of heat in Swedish district heating at 250 SEK /MWh [43].

Among the Baltic States, Estonia is the country with the lowest break-even price (57.5 EUR/MWh) in the absence of economically valued heat output. The PSO accounts for the largest share of the minimum sales price, closely followed by grid costs. In contrast, Latvia is the country with the highest break-even price among the Baltics but also among all countries in the study. Again, the PSO accounts for the largest part of Latvia's break-even price, closely followed by grid costs. A slightly different picture emerges when we analyze the break-even price in Lithuania, which is 78.2 EUR/MWh. In their situation, it is the grid cost what determines the largest share of the marginal cost for the "round trip".

Among all countries, Finland has the highest share of taxes but grid costs account for the largest share of the break-even price (40.4 EUR/MWh). The second lowest break-even price is present in Norway (28.9 EUR/MWh), while the absolute lowest of all is Sweden's (19.7 EUR/MWh). It is worth noting that in the comparison of Norway and Sweden, electricity certificates are part of the cost but it could well be the case that, instead, they are considered part of the revenue – thus helping to improve the business case – because the origin of the electricity in the production of hydrogen is renewable. An important common feature among Denmark, Norway and Sweden is the presence of low taxes applicable to electrolysis. Moreover, grid costs are the lowest in Finland, Norway and Sweden.

The overall picture is somewhat paradoxical: the countries with the best *pre-conditions* for P2G (a developed gas network and high shares of renewables) are the ones that have the *least favorable* framework conditions. Conversely, the countries with the least favorable pre-conditions have the most favorable framework conditions.

Another important message of the quantitative analysis of this sub-section is that even for the lowest break-even price (Sweden), either the input price of electricity would have to be negative or marginal grid costs would have to be reduced even further to make a business case out of a “round trip” application of P2G. On the other hand, creating revenue opportunities from heat sales is another way of increasing the competitiveness of this P2G option.

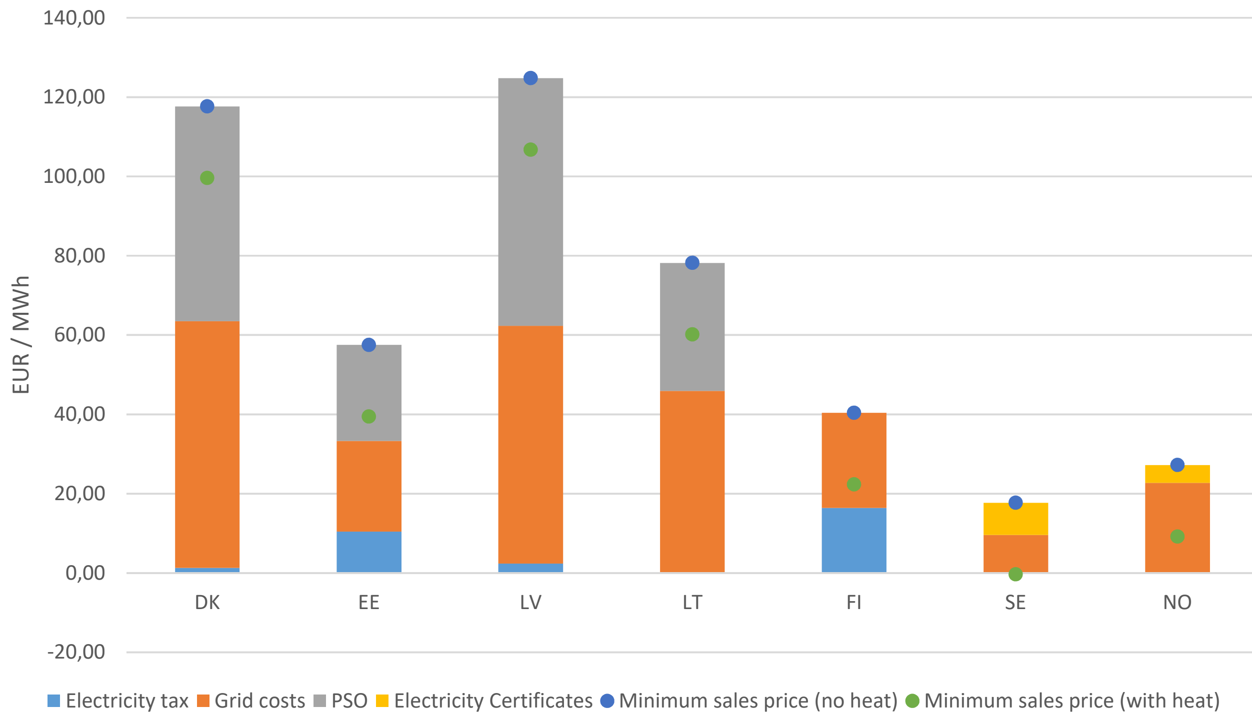

Figure 2: "Round-trip" (electrolysis + fuel cell) marginal costs for 1 MWh of electricity in the Nordic and Baltic countries

5.2 A case study of P2G in Denmark

In this sub-section we focus on Denmark and extend the analysis presented in two ways. First, we make a comparison of electricity generation with two different technologies: a Combined Cycle Gas Turbine (CCGT) vis–à–vis Fuel Cells. Second, we analyze gas upgrading via the methanation of biogas. As before, in both extensions of the analysis we take into consideration the role of taxes, subsidies and grid costs.

5.2.1 Comparing the production cost of electricity: Natural Gas in a CCGT vs. Hydrogen in a Fuel Cell

In this part of the report, we attempt to give an answer to the following question:

- *What makes the difference between the marginal production cost of 1 MWh of electricity from a CCGT running on natural gas vs. a Fuel Cell running on hydrogen in Denmark?*

To this end, we add the following *input cost* entries:

1. *Fuel cost:* for the fuel cost of natural gas, we consider the Danish Neutral Gas price estimated by the Danish gas TSO. Specifically, we chose the price for February 2017 (18.48 EUR/MWh). On the hydrogen side, we estimate the fuel cost of hydrogen produced via electrolysis when the Nordpool system price is 20 EUR/MWh.

2. *Grid costs:* on the side of natural gas, we consider the commodity charge, which depends on the volume of gas, and ignore the exit capacity charge which depends on the capacity booked in the gas transmission system over a longer period of time , i.e. it is levied on market participants that use the gas network frequently. With regards to electricity, we include both TSO and DSO tariffs.

3. *Taxes:* we consider the energy tax together with CO_2 and NOx taxes applicable to natural gas and apply the Danish taxation rules for the simultaneous production of gas and electricity. On the electricity side, we consider the electricity tax under the consideration of "process energy" applicable to the production of hydrogen via electrolysis. In addition – although not a tax per se – we include the Danish PSO under this category.

In addition to the cost entries just mentioned, we consider the economic value of heat, which enters as a *revenue entry* into the calculation. Following the same "rule of thumb" approach mentioned in section 5.1, we assume the same economic value for heat, as before.

The result is shown in Figure 3. Considering the revenue from heat sales, the marginal cost of 1 MWh electricity produced in a CCGT fueled with natural gas is 35.1 EUR/MWh, while it is 146.2 EUR/MWh for the electricity produced via a Fuel Cell running on hydrogen. If the PSO is considered as phased out in Denmark – as will be the case in 2022 – the price decreases to EUR 92.08/MWh and the electricity grid costs account then for the largest component of the marginal cost.

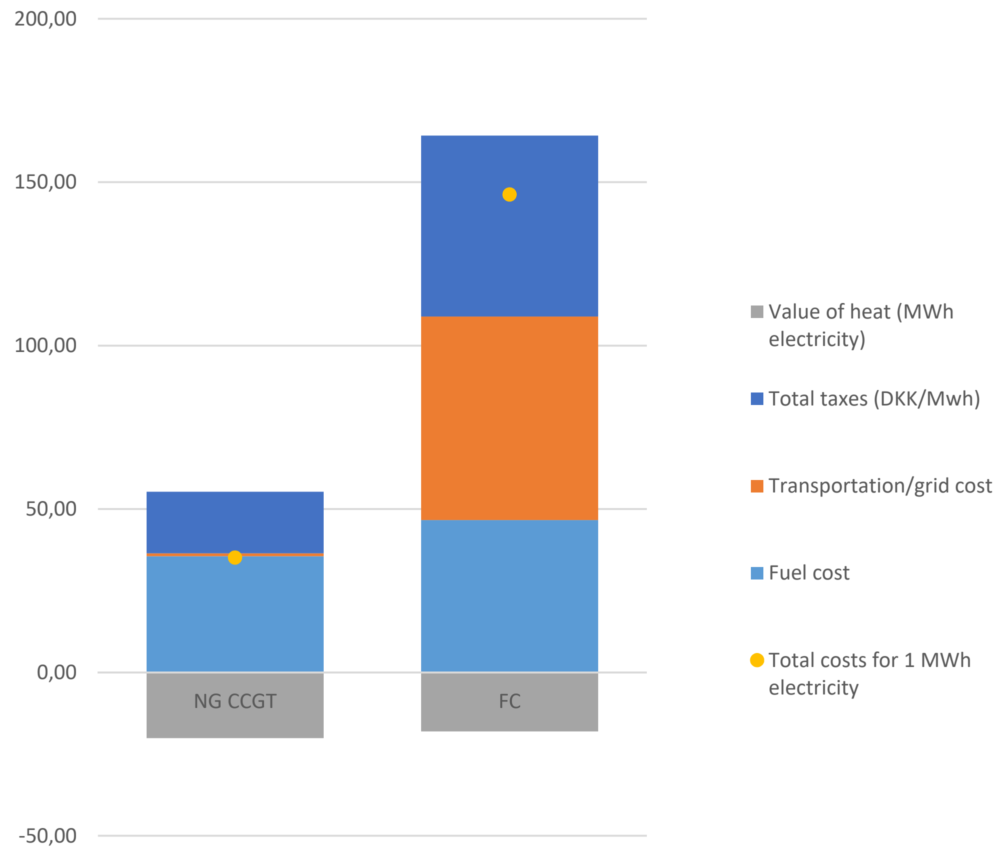

Figure 3: Marginal cost of producing 1 MWh electricity in a CCGT vs. Fuel Cell: The Case of Denmark

In other words, from a technological perspective, it is feasible for hydrogen produced via electrolysis to compete with natural gas but the regulation stands in the way. In particular, there is a dramatic difference between the gas and electricity transportation costs. Moreover, as they stand presently, taxes (including the PSO) send a clear signal in favor of natural gas-fueled electricity output.

5.2.2 Estimating the marginal cost of producing biomethane

Among all countries under consideration in this study, Denmark is the only country that subsidizes gas upgrading. This is an important regulatory approach that, inter alia, attempts to create synergies between biogas production and renewable electricity production in Denmark. Furthermore, it allows utilizing the existing gas infrastructure, enabling flexibility applications in transport and electricity generation in a much easier way.

Other countries in the region, like Finland, which are leaders in the integration of biofuels into their energy systems have, nonetheless, not yet taken a more active approach. Considering this important regulatory development in Denmark, we consider convenient attempting to answer the following question:

- *What is the marginal cost of producing 1 MWh of biomethane in Denmark while considering all applicable taxes, subsidies and tariffs?*

For this purpose, we consider the following input cost entries:

1. *Electricity:* we assume that the system price is 20 EUR/MWh and add to it all applicable taxes, grid tariffs and the PSO, which as of 2017 is in place but will be gradually phased out until 2022.

2. *Biogas*: we use an estimation of the cost of producing biogas in Denmark, as estimated in the models by [44] [45]. This includes all the elements in the biogas value chain *before* upgrading.

In addition to the cost entries just mentioned, we consider the existing subsidy for upgraded biogas [16] as a *revenue* entry.

Figure 4 illustrates the different elements that compose the marginal cost of producing biomethane. Under the previously described assumptions, the largest share (57%) of the total marginal cost of producing 1 MWh of biomethane – 59.7 EUR/MWh *without* subsidy – can be accounted to electricity-related costs, while the rest (43%) corresponds to the cost of biogas. Focusing on the electricity-related costs alone, it is possible to verify that the sum of grid costs plus the PSO account for 23.9 EUR/MWh, that is: 40% of the total cost or more than double the share of the system price (9.6 EUR/MWh) that goes into the total cost. When the subsidy is included in the calculation, the cost is 21.2 EUR/MWh.

Excluding the PSO from the calculation, the total cost without subsidy falls to 48.5 EUR/MWh and including the subsidy, the cost is 10.1 EUR/MWh. However, even in this case, electricity grid costs still account for around one-quarter of the total cost.

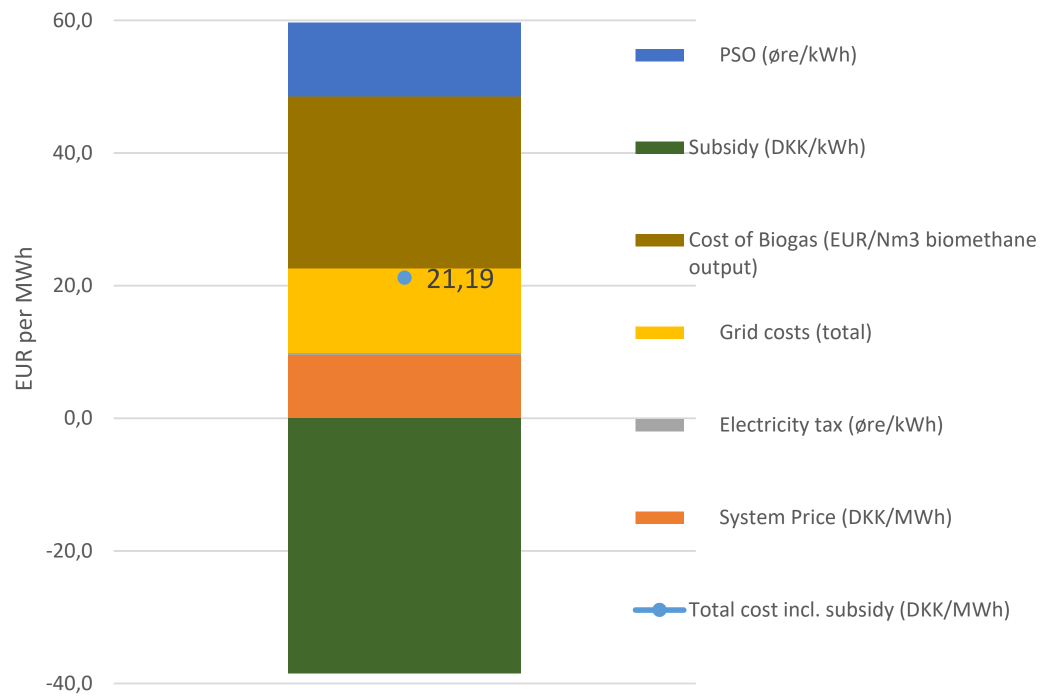

Figure 4: Marginal cost distribution for producing 1 MWh of biomethane in Denmark

But how does biomethane stand in relation to natural gas, and how does the production cost vary in relation to the market price for electricity? The answer is in Figure 5, where the orange line depicts the total cost of biomethane in relation to the electricity price *without* subsidy (horizontal axis). The blue line shows the total cost of biomethane in relation to the electricity price *with* subsidy. The grey line is the price for natural gas in Denmark (more precisely, the Natural Gas price in February 2017), which is independent of the electricity price. Note that the blue and gray lines cross when the price of electricity is 14.4 EUR/MWh. According to these estimations, biomethane is more competitive than natural gas whenever the electricity price is below 14.4 EUR/MWh.

In summary, the analysis of this subsection points to the PSO and grid costs as the main regulatory barriers standing against a more solid business case for biomethane in Denmark.

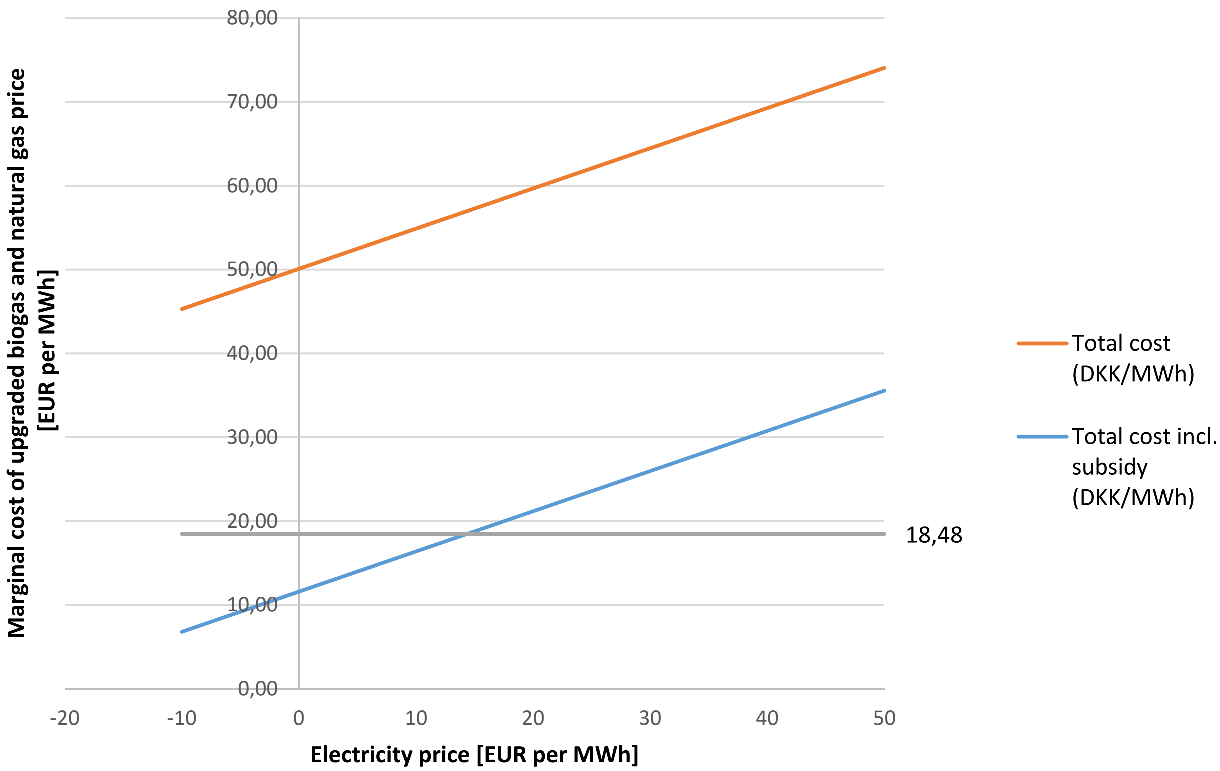

Figure 5: Marginal cost of upgraded biogas (with and without subsidy) vs. Price of natural gas in Denmark

6 Conclusions and policy recommendations

This study has analyzed the framework conditions for P2G in the Nordic and Baltic countries. It has relied on both documental and quantitative analyses of the regulation to determine the drivers and barriers for P2G as a flexibility option.

We have found that P2G is more relevant in countries like Denmark, which possess a well-developed gas network and rely considerably on intermittent sources of generation, like wind power. A similar conclusion can be made in relation to the Baltics, which have favorable system conditions for P2G to be a suitable flexibility option. With the rather mixed electrical capacities and the unequal development of their gas networks, Sweden, Finland and Norway present a more varied set of system conditions.

Regarding framework conditions, the situation in the Baltic States is rather unfavorable for the development of P2G applications. The presence of elevated grid costs and PSO charges stand in the way of the profitable development of the P2G value chain.

Although grid costs and the PSO charge (which will be entirely phased out by 2022) are present in Denmark, it is the “bright spot” of P2G in the region with MW-scale demonstration being run with the support of a combination of both public and private resources. Denmark also has a very favorable taxation framework, which significantly reduces taxes in the electrolysis process. Furthermore, Denmark is the only country that supports the upgrade of biogas via methanation, which is a suitable option for the injection of gas in the existing Danish gas network. Despite the favorable conditions, P2G does not have yet a sufficiently solid business case. We believe that this is due to the presence of substantially high investment costs which could justify the introduction of additional support at the electrolysis stage. This would, among other things, create a more solid business model.

Paradoxically, the countries with *less* favorable system conditions, have *more* favorable framework conditions. Sweden, Norway and Finland have the lowest (per-unit of energy) grid costs and do not have PSO charges. Moreover, Sweden and Norway have a joint, technologically-neutral support scheme in which P2G applications could be easily incorporated.

Finally, based on the whole report, but particularly on the quantitative analysis, we are in a position to make some *tentative* policy recommendations which would help to tackle some of the main barriers we have identified:

- As a *primary* measure, it is convenient to focus on the structure and level of grid tariffs and PSO charges in order to strengthen the business case of P2G applications. These are significantly high in the Baltic States and Denmark. Phasing out the PSO in Denmark, which will be a reality in 2022, is a favorable measure which will strengthen their business case in this country.

- A *secondary* measure, once grid tariffs and PSO charges are reformed, would be to consider providing subsidies to reduce the operational cost in any of the steps of the P2G value chain. An alternative to this measure would be subsidizing the investment cost of P2G-related infrastructure.

- Countries like Finland, which already are leaders in biofuel development, may benefit from supporting gas upgrading activities, like methanation. In other words: Finland could adopt a similar approach to Denmark, where both biogas (an input to methanation) and gas upgrading via methanation are subsidized.

- All the other countries should determine through dedicated studies – as Sweden is already doing in the context of open discussions – the extent to which P2G applications are relevant and the exact applications that it should focus on.

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8 Appendix: Internet links related to the Quantitative Analysis section

The following is a list of links, where the interested reader may obtain the quantitative information for each country:

Nordpool System price: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly/?view=table

Taxes:

- In Denmark: https://www.pwc.dk/da/publikationer/2017/pwc-afgiftsvejledning-2017.pdf
- In Estonia: https://www.riigiteataja.ee/akt/124122016020?leiaKehtiv#para19
- In Finland: https://www.vero.fi/sv-FI/Detaljerade_skatteanvisningar/Punktskatter/Energibeskattning
- In Latvia: https://likumi.lv/doc.php?id=150692
- In Lithuania: https://finmin.lrv.lt/en/competence-areas/taxation/main-taxes/excise-duties
- In Norway: http://www.skatteetaten.no/globalassets/saravgifter/avgiftsrundskriv/2016-elektrisk-kraft.pdf
- In Sweden: https://www.skatteverket.se/foretagochorganisationer/skatter/punktskatter/energiskatter/energiskattpael.4.15532c7b1442f256bae5e4c.html

Grid costs:

- In Denmark: http://www.energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/Sider/Aktuelle-tariffer-og-gebyrer.aspx and http://www.radiuselnet.dk/elkunder/tariffer-afgifter-og-vilk%C3%A5r/tariffer-og-netabonnement
- In Estonia: http://www.konkurentsiamet.ee/file.php?28747
- In Latvia: http://www.ast.lv/lat/pakalpojumi/parvades_pakalpojumu_tarifs/ and https://www.sprk.gov.lv/uploads/doc/ASSadalestklstarifi.pdf
- In Lithuania: http://www.regula.lt/elektra/Puslapiai/tarifai/elektros-energijos-perdavimo-paslaugos-kainos.aspx and http://www.regula.lt/elektra/Puslapiai/tarifai/persiuntimo-tarifai-galioje-iki-2016-m--gruodzio-31-d.aspx
- In Norway: Own calculations based on data collected from Norwegian grid companies. The grid tariff is calculated as an unweighted average of both prioritised and non-prioritised grid connections.
- In Sweden: Own calculations based of data of Swedish Energy Inspection (2014). The variable grid cost is estimated as mean of variable, energy-based tariffs for 1 MW and 20 MW installations.

PSO charges:

- In Denmark: http://www.energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/Sider/Aktuelle-tariffer-og-gebyrer.aspx
- In Estonia: http://elering.ee/taastuvenergia-tasu/

- In Latvia: https://www.sprk.gov.lv/jaunums/obligata-iepirkuma-komponensu-oik-kopeja-vertiba-no-2017-gada-1-aprila-nemainas
- In Lithuania: http://www.regula.lt/en/Pages/public-service-obligation.aspx

Biogas and methanation subsidies:

- In Denmark: http://www.energinet.dk/EN/GAS/biogas/Stoette-til-biogas/Sider/Biogas-PSO.aspx

Electricity Certificate prices:

- In Sweden and Norway: http://www.skm.se/priceinfo/history/2016/

www.Flex4RES.org